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NEW STEPS TOWARDS BETTER DATA AND INVESTIGATION FOR WATER RESOURCES DEVELOPMENT

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NEW STEPS TOWARD BETTER DATA AND INVESTIGATION FOR WATER RESOURCES DEVELOPMENT
by

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Introduction

1. We have learned that the way in which we develop water resources affects the good or ill of mankind. Flow regulation can provide water for irrigation, control floods, or generate power. On the other hand, irrigation can generate salinity problems; the construction of a dam induces changes in river morphology, and the consequences of these changes are costly. Some effects are slow and subtle. Pumping of ground water sooner or later restricts use of river water.

2. Knowledge of such causes and effects -- part of today's slowly gained learning about water development -- is small indeed compared with the vast objectives and problems that lie ahead. To obtain water one must know the environment, and this knowledge is obtained through hydrologic data and study.

3. The domain of man's activity transects all arcs of the water circle. Hydrologic data are therefore of many kinds -- observations of precipitation, snow cover, surface water, ground water, sediment transport, chemical quality, evaporation, soil moisture, and many others. The certainty of this need for hydrologic data in the accelerating water development throughout the world has created a growing interest in improving methods for collecting these records, for their interpretation, and for their use in solving problems. To illustrate these techniques, we have focused attention on some of the principal hydrologic data on precipitation, surface water, and ground water.

4. Hydrologic observations provide data for many purposes, all of which need to be considered in planning a program. On the other hand, it is not possible to anticipate the nature of all future hydrologic inquiries. Moreover, one cannot afford to defer the collection of hydrologic data or the launching of hydrologic studies until specific questions arise for specific areas and problems. Time--often years--is required to collect adequate data. Experience has proved the necessity for a core program, as in a national basic network that is adaptable to the solution of a wide variety of problems. Methods will be described for the design of such networks.

Precipitation

5. As the source of all fresh water, precipitation is an important hydrologic factor. It is at once the easiest and one of the most difficult hydrologic phenomena to measure.

6. Precipitation at a place can be measured in an open vessel -- the idea is ancient, and records of rainfall extend back nearly two centuries. Variations in the type of rain gauge have been introduced. The three main types are recording rain gauges, for measuring minute-by-minute intensity as well as amount of rainfall;

standard rain gauges, in which the catch is read daily; and seasonal gauges, usually placed in mountainous or remote regions, which store the catch over several-month intervals between readings. National networks must contain all three types of gauges, and the Hydrologic Commission of the World Meteorological Organization is at work to devise principles adaptable to design of such networks.

7. The hydrologic problem, however, is to assess rainfall over an area during short periods of time, as during the development of a flood. In general, the accuracy of an areal assessment is proportional to about the 0.6 power of the number of gauges. This means that the number of gauges must increase faster than accuracy, so that to obtain reliable estimates a rather dense network becomes necessary. And even if such a dense network were attainable, there remains the problem of obtaining current information during the progress of a storm. These are the factors that make accurate measurement of the areal distribution of precipitation difficult.

8. Radar equipment has been developed to meet these hydrologic and associated meteorological needs. 1/ Adequate radar equipment used by experienced operators cannot only provide an instantaneous picture of rainfall intensity, but also furnish data for extrapolating a few total-catch gauge measurements into an accurate storm isohyetal map. Furthermore, radar permits estimates of rain intensity and total storm precipitation to be made over terrain where standard rain gauges are impractical.

9. The ability of weather radar to sense rainfall depends on the interaction of high-frequency electromagnetic waves and water drops in the atmosphere. When a high-frequency radio wave impinges on a parcel of air containing water drops, some energy is scattered in all directions by individual drops and some passes through. The net effect of a cloud of particles on a high-frequency radio wave is to reflect some energy and pass some through. The ratio of energy reflected and of energy passing through to the initial energy of the wave depends on frequency of the wave, number of droplets, size of droplets, and size of cloud.

10. The maximum practical range of a radar set is limited by the earth's curvature. Although refraction of the radio waves in the atmosphere bends the transmitted rays slightly below the optical line of sight, the net result is that the center of a radar beam rises to an elevation of 15,000 feet at 160 nautical miles. Thus there is a practical limit to the maximum range of a radar set, because increases in range from increases in transmitter power result in loss of distant echoes from lower elevations.

11. The oscilloscope screens of the U. S. Weather Bureau WSR-57 radar (figure 1) have phosphorescence with persistence that indicates a time-average picture of conditions. The indicator displays may be visualized by considering the signal indications that would come from a hypothetical metal sheet suspended in the sky. Thus, the "P.P.I." scope displays a circular map of echoes centered about the radar set, the "A" scope shows the distance to and intensity of echoes, and the "R.H.I." scope shows a vertical view of the echoes along an azimuth.

12. The radar operator may use either of two methods for recording the areal distribution and intensity of rainfall. He may mark the areal limits of the storm and the isoecho patterns on a transparent sheet placed over the P.P.I. score (overlay method) or he may use a camera to photograph the P.P.I. scope (multiple-exposure method). The record of the storm consists of maps or photos taken at equal intervals during the time the storm is within range of the set.

1/ U. S. Weather Bureau: The radar program of the U. S. Weather Bureau, Washington (1961).

Ground Water

13. During the past decade, important emphasis has been given to the development of ground water in the newly emerging nations, particularly those in the arid regions of the world. Optimum utilization of the resource demands adequate appraisal through collection of relevant data by appropriate surveys and the analysis and synthesis of such data, both before and subsequent to development. Ground water, of course, is a phase of the hydrologic cycle, but the investigation of this water involves techniques and methods that may be distinctly different from those appropriate to other phases of the cycle.

14. The techniques employed in ground-water investigations depend in large measure on the relative sophistication, complexity, and scope of the actual or proposed development of a ground-water system. A total evaluation might include surface and subsurface geological, surface and subsurface geophysical, geochemical, hydraulic, and hydrologic studies. However, a simpler ground-water investigation might include only a few selected elements from among these. Good aerial photography and topographic maps are fundamental to all surveys related to ground water. Also, as the rocks are the natural reservoirs in which ground water is stored and the natural conduits through which it circulates, knowledge of the geologic framework of a ground-water system is essential to its understanding.

15. In recent years, geophysical studies have been used to increasing extent in quantitative and semiquantitative evaluations of ground-water systems. Among surface geophysical methods, electrical-resistivity, seismic, aeromagnetic, gravimetric, and sonar surveys are employed with varying degrees of success. Surface electrical-resistivity surveys are used successfully in one-, two-, and even three-layer systems, where marked discontinuities occur in the electrical-resistivity profile and where the thickness of each layer is appreciable in relation to the depth of the depth of the discontinuity. Such surveys are particularly useful in establishing fresh water-salt water interfaces in coastal aquifers. Seismic surveys are used mainly to map discontinuities between impermeable bedrock and overlying water-bearing unconsolidated or semiconsolidated sediments. The method is adequate only where there is a marked contrast in the elastic properties of the two types of rock. Aeromagnetic and gravimetric methods are also used to locate buried bedrock surfaces where appreciable discontinuities in rock magnetism and density exist in two-layer systems. Although these methods are not widely used in ground-water problems in the United States, they have found considerable application in countries of the Eastern Hemisphere. Aeromagnetic methods are particularly useful where rapid reconnaissance delineation of aquifers is required over broad regions. Mapping of bedrock surfaces and thickness of unconsolidated overlying deposits by techniques and equipment using low-frequency sound waves also is finding increasing application, particularly in underwater problems in coastal areas. The principles employed are the same as those used in sonic depth finders.

16. Subsurface or borehole geophysical methods are now widely employed in practically all moderately intensive or detailed ground-water investigations. Electrical logging is perhaps the most useful tool in distinguishing aquifer contacts, formational porosity, water quality, and fresh-salt water interfaces in uncased boreholes. Also this method can be used quantitatively, if other supplementary field data are available. Gamma-ray and neutron logging is also increasingly used for stratigraphic correlation, particularly between cased wells. However, proper interpretation of such radiation logs requires considerable antecedent knowledge of the local lithology. Limestones and dolomites, for example, have radioactive intensities similar to sandstones.

17. The importance of depth-temperature relations in ground-water systems is

increasingly recognized, particularly with respect to water viscosity and the effective permeability of aquifers. An important tool in the analysis of these relations is the temperature log, which utilizes conventional electric logging circuits to measure resistance change of a temperature-sensitive metallic conductor. By this method, which can be used in both cased and uncased wells, a temperature log and a corresponding reciprocal-gradient log are derived. From these logs it is possible to identify the aquifer or aquifers tapped by wells. Borehole diameter or caliper logging is an important tool in long-range stratigraphic or aquifer correlation. The caliper log is also used to determine the condition of an under-reamed section of a borehole prior to placement of a gravel pack and well casing, and to estimate the volume of cement necessary to fill the annular space between the well casing and the borehole wall. This technique is based on variation of borehole diameter which reflects differences in the lithologic character of the rocks penetrated by the drill. Another borehole technique of wide application is flow-meter logging which provides a record of the velocity and direction of movement of water in a well. The log may be made while the well is discharging water at the land surface, while water is being introduced, or while the well is idle. The flow-meter log serves to identify and evaluate the aquifers tapped by cased wells having multiple screens, leaks in cased wells, and permeable zones penetrated by cased wells. Still another borehole technique is fluid-conductivity logging which provides a record of the electrical conductivity of the borehole fluid at all depths. Such a log provides useful information on the position of salt-water leaks in cased artesian wells and the depth and relative artesian head of salt-water aquifers penetrated by cased wells. Still more recently, compact television cameras with wide-angle lenses of short focal length are being designed for on-site inspection of well casings and examination of the lithologic character of borehole surfaces.

18. Perhaps the most sophisticated technique now in use in the laboratory analysis of simulated ground-water systems is the passive-element analogue model which is based on the direct analogy between electric and fluid force fields. (See Figure II.) For any ground-water system, an analogue model employing resistor-capacitor networks with analyzers can be constructed, with a degree of complexity depending on the nature of the ground-water system and the available basic data. In the model, the fundamental aquifer variable (transmissibility) is simulated by an electrical variable (conductance), and aquifer storage is simulated electrically by capacitance. The electric analogue model affords a useful means for computing the distribution of potential (or head) at any point in the system under complex boundary conditions as well as variable recharge and withdrawal by pumping.

19. The chemical characteristics of ground water are very important with respect to its utilization as well as with respect to geochemical methods for analyzing ground-water systems. Identifiable chemical constituents in minute concentration are particularly useful in tracing the direction and velocity of water movement through the rock skeleton but must be used in conjunction with adequate geologic and hydrologic knowledge of the ground-water system. Induced tracers such as salt solutions, fluorescein, and radioactive materials commonly are used for this purpose. Also radioisotopes, such as carbon-14 and tritium, are proving useful in determining the relative age of water in different parts of a ground-water system and the span of the "life cycle" of such a system. Chemical quality and temperature relationships also enter into the quantitative evaluation of other ground-water problems, including salt-fresh water relationships in coastal aquifers, base exchange, influx of mineralized waters or brines, aquifers as heat exchangers, induced infiltration, artificial recharge, and disposal of radioactive wastes.

20. Because of the importance of the transmission and storage characteristics in the hydraulic behaviour of aquifers and ground-water systems, a considerable number of methods have been evolved for the mathematical analysis of problems in fluid

mechanics as they apply to ground-water flow systems. To enumerate, well methods of aquifer evaluation include those involving constant discharge or recharge without vertical leakage, instantaneous discharge or recharge, constant head without vertical leakage, constant discharge with vertical leakage, and variable discharge without vertical leakage. Channel or drain methods include those applicable to constant discharge, constant head, and sinusoidal head fluctuations. Numerical analysis and flow-net analysis provide the chief areal methods of aquifer evaluation. Also, the analysis of hydrologic boundary problems has been built on a number of methods involving the theory of images.

21. Quantitative evaluation of ground-water systems by hydrologic methods has had a considerably longer history of evolution in the United States than the development and use of hydraulic methods. Appraisal of the ground-water resource requires an accounting of the perennial intake, discharge, and changes in storage with relation to man's existing and future needs for ground-water supplies. In addition, water quality must be adequately defined with regard to temporal and spatial changes in ground-water systems and the effects of such changes on man's use of the water. Among the seepage methods for evaluating the recharge-discharge balance in ground-water systems are seepage surveys keyed to streamflow records from gauging stations and analysis of stream hydrographs, the base-flow hydrograph analysis, and water-budget studies. Methods for estimating recharge or discharge from changes in ground-water storage include lysimeter or tank studies, observation-well hydrographs, isopachous maps of net change in water level, saturation or drainage techniques, and indirect methods. In all storage methods, specific yield must be known to convert changes in storage volume to water volume.

Surface Water

22. A most significant development in the collection of hydrologic data in the United States in the past decade has been that of a digital recorder for the measurement of river stages. These instruments punch a digitized record of water level on a paper tape in a manner compatible with systems of computation by high-speed digital computers. The records may be used with any of several stage-sensing devices -- floats, pressure transducers, or gas-purge (bubble gauge) systems of head-pressure sensing.

23. The records-processing program begins with a stage record obtained from a digital-recorder gauge (see Figure III) and ends with a computer print-out listing mean daily discharge rates, computed monthly and annual averages, maximum and minimum rates of flow during monthly and annual periods, and flood-hydrograph data for floods meeting preselected criteria.

24. The entire processing procedure is called a "gauge to page" plan, for almost the entire process is accomplished by the use of machines, the only human factor being the introduction of judgment factors into the programming of computer operations. The print-out from the computer is ready for reproduction by photographic methods for formal publication.

25. The procedure, in brief, begins with a stage-sensing device installed at the gauging site on a river, which activates a digital recorder to punch a digitized record of stage on a paper tape. This record on paper tape is translated by machine to magnetic tape in appropriate computer language. A program is designed for a high-speed computer which takes the magnetic tape, combines it in the computer operations with the programmed commands for stage-discharge relationships and the desired discharge products, and proceeds to perform all commanded operations and print out the results. Using the techniques described, it is now possible to compute a year's record in only a few minutes, whereas the same operations performed

by hand require many hours.

26. A second significant development in the collection of river data in the United States is the invention of a stage-sensing device called a "bubble gauge." This gauge (Figure IV) was developed to record reservoir and river levels without the use of stilling wells and intake pipes, which are often expensive to construct and difficult to maintain. The gauge consists of a specially designed servomanometer, a transistorized control, a gas-purge system, and a recorder. The pressure corresponding to the head of water is brought to the manometer by the gas-purge system. Nitrogen gas is discharged slowly through plastic tubing from the gauge house to an orifice located at a fixed elevation in the stream. The pressure at the orifice, and hence at any point in the delving tube, is related to the head or depth of water over the orifice. This pressure is in turn transferred to the manometer and then to the recording device. The manometers have a sensitivity of ± 0.005 foot, and the entire assemblage can be constructed to record ranges in stage in excess of 120 feet. A differential type of manometer may be adapted to the instruement to record directly the slope in a short reach of river channel.

27. Several new field instruments are undergoing development and field tests in the United States, and will soon significantly influence data-collection techniques. One of these is a velocity meter based on measurement of the electromagnetic effect of flowing water. This meter will generally be adapted to the continuous measurement of water velocity at preselected points. An acoustic velocity meter is being tested, which will measure the mean velocity in a line across a stream channel. The meter is based on the Doppler principle and relates water velocity to the difference in travel time of ultrasonic waves moving in opposite directions between transducers located across the stream from each other and offset from each other in a longitudinal direction. We are also attempting to develop a small portable current meter based on the Doppler principle. The Doppler effect is evident in a change in frequency of an emitted signal due to motion of the water and suspended sediment with respect to the meter. The meter, which gives a direct reading of velocity, appears to be particularly applicable to the measurement of very low stream velocities. The instrument will be fully transistorized and battery-powered, resulting in a light portable device admirably suited to use by field personnel.

28. A special depth-sounding and velocity-measuring device has been developed for measuring extreme flood flows. This instrument combines a fathometer, a direction compass, and a Price current meter, and permits measurements of depth, direction of current, and near-surface velocity with a single setting and without encountering the hazards of complete depth sounding by sounding weight. The technique of augmenting continuous flood records by operation of only crest-stage gauges has been enhanced by the development of a small, cheap ($50) water-stage recorder. This recorder may be operated intermittently in a 3-inch pipe well to obtain only flood hydrographs.

29. Streamflow data-collection programs in the United States include provision for determinations of suspended sediment and chemical quality of river flow. Water-temperature measurements are a routine part of water-quality observations. As in the collection of flow data, techniques for collection and analysis of water samples have been refined in recent years. Newer methods for chemical analysis of water include such instrumental techniques as spectrophotometry and flame photometry. Increasing emphasis is being given to development of techniques for measuring trace elements. During recent years several models and sizes of depth-integrating samplers have been developed to permit accurate and efficient sampling of sediment suspended in river flow. A depth-integrating sampler is moved vertically through the sampling zone at a constant rate and admits a water-sediment mixture at a velocity about equal to the stream velocity at all points of its travel. Other samplers have been

developed to sample continuously at a point, and to collect bed material for particle-size examination.

30. Much effort is being expended in the United States in the development of techniques of analysis for the generalization and synthesis of streamflow data. It is never possible to collect information at all potential sites of need. The problem usually faced requires generalization of existing data in such manner as to form a basis for the synthesis of flow data at ungauged sites to acceptable limits of accuracy.

31. Perhaps the most difficult problem facing water-data program planners is the design of adequate networks for the collection of field measurements. Intuitive and judgment factors are utilized in beginning such networks. Appropriate weight is given to sampling areas having differing terrains, geology, and climate, and to existing needs for data at specific sites. As techniques are improved, and the needs for data increase, networks are expanded.

32. Several years ago the network of streamflow and water-quality guaging stations in the United States had grown to such proportions that it was necessary to evaluate the entire program. The principal classifications of stations derived from this and subsequent studies follow: (1) primary stations, those having essential hydrologic significance and operated for indefinitely long periods; (2) secondary stations, those at which continuous flow records are obtained for a period of only a few years (5 to 10); and (3) partial-record stations, those at which flows, or stages, are measured only during extremes of either high or low conditions.

33. In testing the existing design of primary gauging stations, statistical methods were used to determine the degree of independence of stations in the network. With these criteria it was possible to eliminate some stations and to pinpoint new areas needing gauging. Thus, the optimum extent of the required primary network was determined.

34. The principal rationale in the use of networks of secondary and partial-record stations is to obtain a maximum amount of data at minimum cost. Modern statistical methods in hydrology permit records from these shorter or less complete operations to be extrapolated to accurate estimates of flow parameters for longer periods. Networks of such stations become more dense as water development proceeds in an area and the need for more detailed hydrologic information increases.

35. A final consideration in the responsibility of a government to furnish hydrologic data for its own use and that of its citizens is the preservation of the data in a place and in a form useful and available to all. Our emphasis in the United States is on data accurate by high technical standards, centrally filed, permanently preserved, and readily available. High consideration is given to the introduction of new techniques where they have promise of adding accuracy or decreasing costs. Much of what has been learned is directly applicable to the newly developing countries.

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ANNEX I

Fig. I - Major Components of the WSR-57 radar

Fig. II - Passive element analogue model showing oscilloscope, input generator, and resistor-capacitor network of San Simon Basein, Arizona.

Fig. III - Digital Recorder

Fig. IV - Baubble Gauge to register river levels

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